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RHIC STATUS AND PLANS*

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Abstract

RHIC is the first hadron accelerator and collider consisting of two independent rings. It is designed to operate over a wide range of beam energies and with particle species ranging from polarized protons to heavy ions. Machine operation and performance will be reviewed that includes gold-on-gold collisions at design beam energy (100 GeV/u), first high energy polarized proton-proton collisions (100 GeV on 100 GeV) as well as first asymmetric operation of RHIC to produce deuteron-on-gold collisions. Plans for future luminostiy upgrades will also be presented.

THE RHIC FACILITY

With its two independent rings RHIC is a highly flexible collider of hadron beams ranging from colliding intense beams of polarized protons to colliding fully stripped gold ions. The collision of 100 GeV/nucleon gold ions probes the conditions of the early universe by producing extreme conditions where quarks and gluon are predicted to form a quark-gluon plasma - new state of matter.

The RHIC polarized proton collider will open up the completely unique physics opportunities of studying spin effects in hadronic reactions at high-luminosity high-energy proton-proton collisions. It will allow study of the spin structure of the proton, in particular the degree of polarization of the gluons and anti-quarks, and also verification of the many well-documented expectations of spin effects in perturbative QCD and parity violation in W and Z production. The RHIC center-of-mass energy range of 200 to 500 GeV is ideal in the sense that it is high enough for perturbative QCD to be applicable and low enough so that the typical momentum fraction of the valence quarks is about 0.1 or larger. This guarantees significant levels of parton polarization.

During its first three years of operation RHIC has already operated close to design parameters for gold-gold collisions[1], had a very successful operating period of deuteron-gold collisions with both beams at the same energy per nucleon but, of course, different rigidity, and two short but very successful running periods with polarized protons. RHIC was operating for all of these runs with beam energies of 100 GeV/nucleon - the gold beam design energy.

GOLD-GOLD OPERATION

Fig. 1 shows the layout of RHIC and the three injector accelerators Tandem, Booster and AGS. The gold ions are stepwise ionized as they are accelerated to RHIC injection energy, at which point they are fully ionized. The performance of the injector[2] is summarized in Table 1. The Tandem Van de Graaff accelerates Au^{-1} from a sputter source to about 1 MeV/nucleon. The 530 ms long beam pulse is stripped to Au^{+32} and injected into the Booster using horizontal and vertical phase space painting. After acceleration to about 100 MeV/nucleon the beam is stripped to Au^{+77} and transferred to the AGS where it is accelerated to the RHIC injection kinetic energy of 8.6 GeV/nucleon. In the AGS the beam bunches from the Booster are merged to reach the required intensity of about 1×10^9 Au ion per bunch at a longitudinal emittance of 0.3 eVs/nucleon. The final stripping to bare Au^{+79} occurs on the way to RHIC.

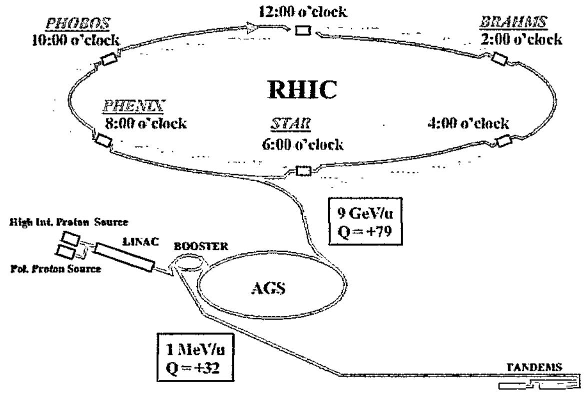

Figure 1: Layout of RHIC and the injector accelerators. The gold ions are stepwise ionized as they are accelerated to RHIC injection energy.

RHIC is the first super-conducting, slow ramping accelerator that crosses transition energy during acceleration. At transition energy the spreads of the particle revolution frequency stemming from the spread in velocity and spread in path length cancel exactly and all particles maintain their relative position for a long time. Interaction between parti-

Table 1: RHIC injector performance

Location	RHIC bunch intensity	Efficiency
Tandem	5.4×10^9	
Booster Injection	2.9×10^9	54%
Booster Extraction	2.4×10^9	83%
AGS Injection	1.2×10^9	50%
AGS Extraction	1.1×10^9	92%
Total		20%

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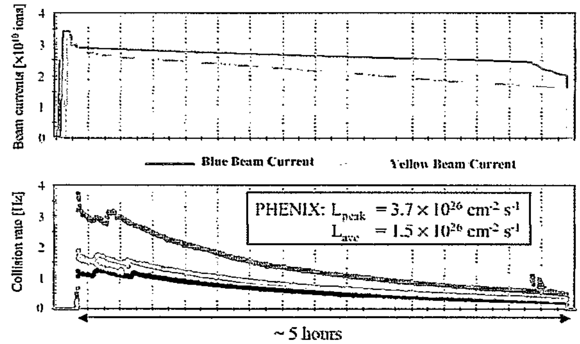

Figure 2: Evolution of the collision rate at the four RHIC detectors during a typical store. The intensity drop at the end of the store is due to the removal of the beam in the abort gap.

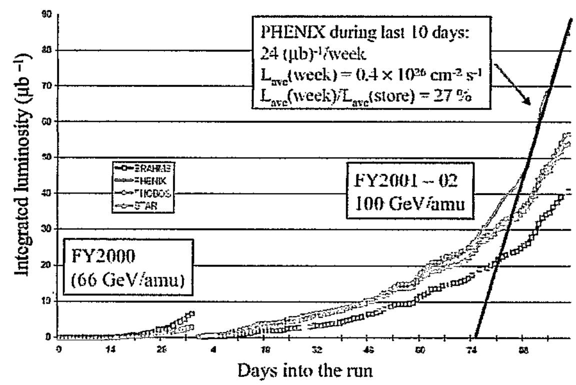

Figure 3: Integrated luminosity of the four RHIC experiments.

cles can then cause instabilities. With pulsed quadrupole power supplies the transition energy is changed quickly during acceleration to effectively jump across it. The dispersion distortion required to change the transition energy is local and the betatron tune shift is corrected in a zero-dispersion region[3]. This scheme allows for up to 1 GeV change in transition energy with very little lattice distortion.

The two RHIC rings, labelled blue and yellow, are intersecting at six interaction regions (IR), four of which are occupied by the collider experiments BRAHMS, STAR, PHENIX and PHOBOS. All IRs can operate at a betastar between 2 and 10 m. In two interaction regions (STAR and PHENIX) the quality of the triplet quadrupoles allows further reduction of betastar to 1 m. During this run betastar was 10 m at injection energy for all IRs and was then squeezed during the acceleration cycle to 1 m for PHENIX, 2 m for the other experiments and 10 m in the remaining two IRs. A typical acceleration cycle consists of filling the blue ring with 56 bunches in groups of 4 bunches, filling the yellow ring in the same way and then simultaneous acceleration of both beams to storage energy. During acceleration the beams are separated vertically by about 10 mm in the interaction regions to avoid beam losses from the two beams colliding.

Typical stores lasted about 5 hours. Fig. 2 shows the evolution of the collision rate in the four experiments during a typical store. After optimizing longitudinal and transverse steering the initial observed luminosity at PHENIX was about $3.7 \times 10^{26}\ cm^{-2}\ s^{-1}$ with an average luminosity over the 5 hour store of $1.5 \times 10^{26}\ cm^{-2}\ s^{-1}$, which is close to the design average luminosity . This corresponds to an initial normalized 95% beam emittance of about $15\pi\ \mu m$ growing to about $30\pi\ \mu m$ at the end of the store. The beam loss and transverse emittance growth during the store is mainly caused by intra-beam scattering, which is particularly important for the fully stripped, highly charged gold beams[4].

The collision rate was measured using identical Zero Degree Calorimeters (ZDC) at all four interaction regions. The ZDC counters detect at least one neutron on each side from mutual Coulomb and nuclear dissociation with a total cross section of about 10 barns[5]. The overall average luminosity for PHENIX during the last 10 days of the run was $0.4 \times 10^{26}\ cm^{-2}\ s^{-1}$ which gives an effective running efficiency of 27%. The integrated luminosity over the run is shown in Fig. 3 and exceeded 80 $(\mu b)^{-1}$ for PHENIX.

The gold beam intensity were limited mainly by vacuum break-downs in the room temperature sections of the RHIC rings[6][7]. Possible explanations for this process include gas desorption from halo scrapping and/or electron multipacting driven by the gold beam bunches. Gas desorption and electron production is very large for gold ions striking the vacuum chamber at a glancing angle. The situation can be greatly improved by baking all room temperature sections to a residual gas pressure of less than 10^{-10} Torr.

The bunch intensity was also limited by a very fast single bunch transverse instability, shown in Fig. 4, that develops near transition where the chromaticity needs to cross zero. It could be stabilized using octupoles. This instability has a growth rate faster than the synchrotron period and is similar to a beam break-up instability[9].

DEUTERON GOLD OPERATION

During the last running period RHIC was operating for the first time with asymmetric collisions[10]. Colliding 100 GeV/nucleon deuteron beam with 100 GeV/nucleon gold beam will not produce a quark-gluon plasma and therefore serves as an important comparison measurement to the gold-gold collisions. The rigidity of the two beams is different by about 20%, which results in different deflection angles in the beam-combining dipoles on either side of the interaction region as shown in Fig. 5. This requires a non-zero angle at the collision point, which slightly reduces the available aperture.

The injection energy into RHIC was also the same for both beams requiring the injector to produce beams with different rigidity. With same energy beams throughout the acceleration cycle in RHIC the effect of beam collisions could be minimized. Typical bunch intensity of the deuteron beam was about 1.2×10^{11} with emittances of about 12 $\pi\mu m$ [norm., 95%] and 0.3 eVs/nucleon. The gold beam parameters were similar to the gold-gold operation described above. The high intensity deuteron beams required careful adjustment of the chromaticity, especially around transition, to avoid transverse instabilities. A peak luminosity of 6.2×10^{28} cm^{-2} s^{-1} and store-averaged luminosity of 2.8×10^{28} cm^{-2} s^{-1} was reached at the IRs with the 2 m betastar.

POLARIZED PROTON COLLISIONS

Fig. 8 shows the lay-out of the Brookhaven accelerator complex highlighting the components required for polarized beam acceleration[11][12]. The new 'Optically Pumped Polarized Ion Source'[13] is producing 10^{12} polarized protons per pulse. A single source pulse is captured into a single bunch, which is ample beam intensity to reach the nominal RHIC bunch intensity of 2×10^{11} polarized protons.

In the AGS a 5% solenoidal partial snake that rotates the spin by 9° is sufficient to avoid depolarization from imperfection resonances up to the required RHIC transfer energy of about 25 GeV. Full spin flip at the four strong intrinsic resonances can be achieved with a strong artificial rf spin resonance excited coherently for the whole beam by driving large coherent vertical betatron oscillations. The remaining polarization loss in the AGS is caused by coupling resonances and weak intrinsic resonances. Faster acceleration rate and a future, much stronger partial Snake should eliminate depolarization in the AGS.

The full Siberian snakes (two for each ring) and the spin rotators (four for each collider experiment) for RHIC each

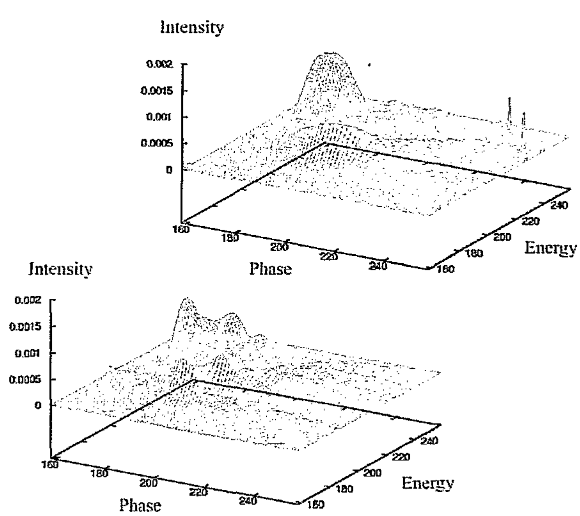

Figure 4: Tomographic reconstruction of a gold bunch before (top) and after a fast transverse instability[8].

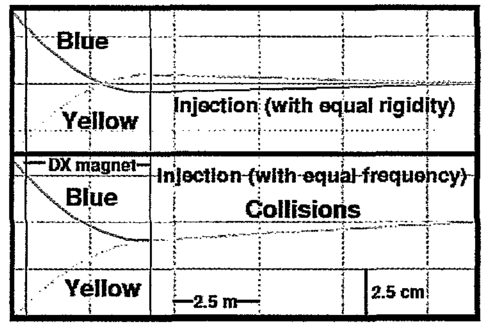

Figure 5: Orbits of the gold and deuteron beams through the beam-combining dipole that is located on either side of the IR. The top figure shows the initial geometry at injection with equal beam rigidities. The bottom figure shows the collision geometry with equal beam energies. Equal energy was later also used at injection to avoid beam loss from beam-beam induced tune modulations.

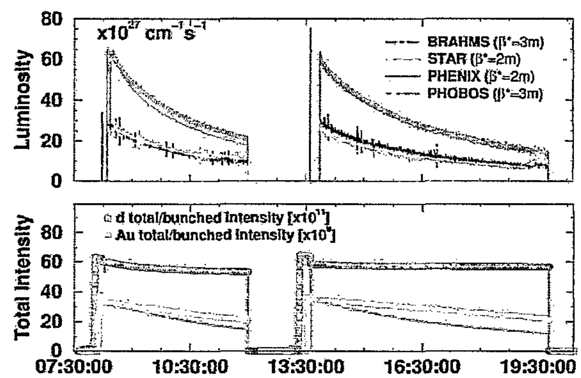

Figure 6: Evolution of the luminosity and beam intensities at the four RHIC detectors during two typical deuterium-gold stores.

consist of four 2.4 m long, 4 T helical dipole magnet modules each having a full 360° helical twist. The 9 cm diameter bore of the helical magnets can accommodate 3 cm orbit excursions at injection. Fig. 7 shows the orbit and spin trajectory through a RHIC snake. The super-conducting helical dipoles were constructed at BNL using thin cable placed into helical grooves that have been milled into a thick-walled aluminum cylinder[14].

In addition to maintaining polarization, the accurate measurement of the beam polarization is of great importance. Very small angle elastic scattering in the Coulomb-Nuclear interference region offers the possibility for an analyzing reaction with a high figure-of-merit which is not expected to be strongly energy dependent[15]. For polarized beam commissioning in RHIC an ultra-thin carbon ribbon was used as an internal target, and the recoil carbon nuclei were detected to measure both vertical and radial polarization components. The detection of the recoil carbon with silicon detectors using both energy and time-of-flight information showed excellent particle identification. It was demonstrated that this polarimeter can be used to monitor polarization of high energy proton beams in an almost non-destructive manner and that the carbon fiber target could be scanned through the circulating beam to measure polarization profiles. In the future a polarized gas jet will be installed as an internal target for small angle proton-proton scattering which will allow the absolute calibration of the beam polarization to better than 5 %.

During the first polarized proton collider run in RHIC from Dec. 2001 to Jan. 2002 polarized beams were successfully accelerated to 100 GeV and stored and collided with a peak luminosity of about 1.5×10^{30} cm^{-2} s^{-1}. The beam polarization at the AGS was only about 30% mainly due to the fact that a back-up AGS main power supply had to be used with a much reduced ramp rate that amplified the effect of the depolarizing resonances. However, essentially all beam polarization was preserved during acceleration and beam storage in RHIC. Fig. 9 shows circulating beam current and measured asymmetries of two typical stores. The analyzing power at 100 GeV for the RHIC polarimeters is not known but expected to be similar to the value at injection energy. Under this assumption the polarization at store was typically about 25 %. To preserve beam polarization in RHIC during acceleration and storage the vertical betatron tune had to be maintained between 0.220 and 0.235 and the orbit had to corrected to better than 1 mm rms. This is in good agreement with the predictions from spin tracking calculations.

More than 20 years after Y. Derbenev and A. Kodratenko[16] made their proposal to use local spin rotators to stabilize polarized beams in high energy rings, it has now been demonstrated that their concept is working flawlessly even in the presence of strong spin resonances at high energy.

For the second polarized proton run all eight spin rotators were installed to allow for longitudinal polarization at both PHENIX and STAR[17]. With the nominal acceleration rate the polarization at the AGS was about 45 %. Polarization of up to 35% was reached at 100 GeV and longitudinal polarization was produced at the PHENIX IR. At the store energy of 100 GeV the betastar was squeezed from 10 m to 1 m at STAR and PHENIX and 3 m at BRAHMS

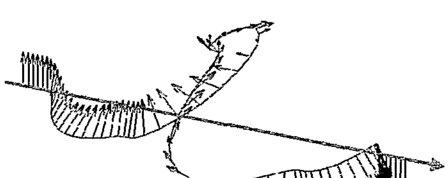

Figure 7: Orbit and spin tracking through the four helical magnets of a Siberian Snake at $\gamma = 25$. The spin tracking shows the reversal of the vertical polarization.

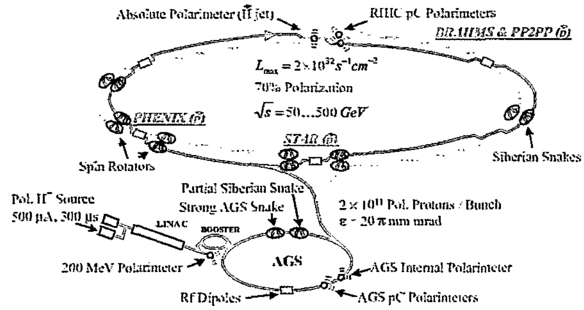

Figure 8: Layout and design parameters for the Brookhaven polarized proton collider. The eight spin rotators and the absolute polarimeter were not installed for this run.

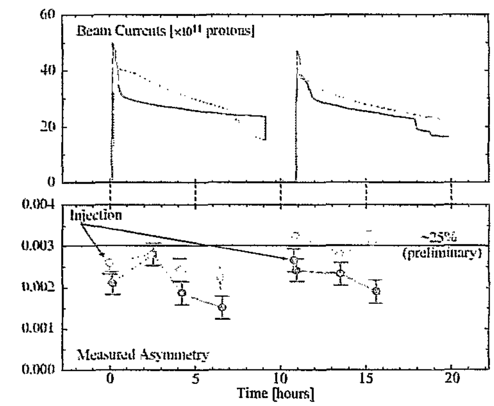

Figure 9: Circulating beam and measured asymmetry in the blue and yellow RHIC ring (blue(dark) and yellow(light) lines and symbols, respectively) for two typical stores.

and PHOBOS. The peak luminosity with 1 m betastar was about 3×10^{30} cm^{-2} s^{-1} with 55 bunches in each ring with a bunch intensity of 0.5×10^{11} and a 95% normalized emittance of about 12 $\pi\mu m$. Note that the beam-beam tune shift parameter under these conditions is about 0.003 for each IR or 0.012 for four IRs with colliding beam[18].

Operation at full collision energy of $\sqrt{s} = 500$ GeV is planned for the future with a luminosity of up to 2×10^{32} cm^{-2} s^{-1}.

RHIC UPGRADE PLANS

An initial upgrade of the RHIC luminosity for heavy ion operation by a factor of four beyond design (2×10^{26} cm^{-2} s^{-1}) can be achieved by doubling the number of bunches to 110 (100 ns bunch spacing) and reducing betastar from 2 m to 1 m. As described above this has already partially been achieved although further progress is required in controlling vacuum break-downs before routine operation with 100 ns bunch spacing is possible.

Even further upgrade of the luminosity requires that the emittance growth from intra-beam scattering is reduced or eliminated. The growth of the beam size due to intra-beam scattering can be overcome by cooling the beams with a high intensity cold electron beam[19]. To cool the 100 GeV/n gold beam with 10^9 ions per bunch in RHIC a 54 MeV electron beam with an average current of about 100 mA is required. In this case the charge of each electron bunch is about equal to the charge of the ion bunch. The high beam power of about 5 MW of the electron beam makes it necessary to recover the beam energy by decelerating it in the super-conducting linac as has been successfully demonstrated at JLab with a 50 MeV, 5 mA electron beam.

Table 2 shows the parameters for future RHIC luminosity upgrades for the first stage without electron cooling and then with electron cooling. Electron cooling has the most dramatic effect on the luminosity of gold collisions. However, it also improves operation with polarized protons due to the lower beam emittance.

Electron cooling of the high energy, heavy ion beams in RHIC extends beyond presently operating electron cooling facilities in several regards: the use of bunched electron beam accelerated by a linear accelerator, beam cooling during collider operation, and the use of a highly magnetized, angular momentum-dominated electron beam to avoid recombination of e^- and Au^{79+}.

An R&D program has started to develop the critical items of the RHIC electron cooling system. The high-brightness, high-current electron source consists of a rf photo-cathode gun operating at 700 MHz capable of providing 2.5 MeV and about 100 mA current. A 700 MHz super-conducting cavity for the energy-recovering linac will be developed that is capable of accelerating the high intensity electron beam without causing beam-breakup. The feasibility of a long, highly uniform super-conducting solenoid for the electron cooling section will be demonstrated with a prototype.

Table 2: RHIC luminosity upgrade with electron cooling.

Gold-gold	w/o e-cool.	with e-cool.
Beam energy [GeV/n]	100	100
Emittance (95%) [$\pi \mu m$]	$15 \rightarrow 40$	$15 \rightarrow 3$
Beta function at IR [m]	1.0	$1.0 \rightarrow 0.5$
Number of bunches	112	112
Bunch population [10^9]	1	$1 \rightarrow 0.3$
Beam-beam param. per IR	0.0016	0.004
Peak lum. [$10^{26} cm^{-2} s^{-1}$]	32	90
Ave. lum. [$10^{26} cm^{-2} s^{-1}$]	8	70
Proton-proton:		
Beam energy [GeV]	250	250
Emittance (95%) [$\pi \mu m$]	20	12
Beta function at IR [m]	1.0	0.5
Number of bunches	112	112
Bunch population [10^{11}]	2	2
Beam-beam param. per IR	0.007	0.012
Lum. [$10^{32} cm^{-2} s^{-1}$]	2.4	8.0

A low emittance cooled gold beam in RHIC will also be essential for a future electron ion collider at RHIC. A high current 10 GeV polarized electron beam would be collided with the 100 GeV/n cooled gold beam or the 250 GeV polarized proton beam a RHIC interaction region with luminosities of $5 \times 10^{30}\ cm^{-2}\ s^{-1}$ (eAu) and $0.5 \times 10^{33}\ cm^{-2}\ s^{-1}$ (ep).

ACKNOWLEDGMENT

The highly successful commissioning and early operation of RHIC was made possible by the excellent and dedicated RHIC design, construction, and commissioning team.

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